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GRAIN BREAKAGE CAUSED BY COMMERCIAL HANDLING METHODS

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PREFACE

This publication reports the results of a comprehensive study conducted by Cargill, Inc., under Research Contract No. 12-14-100-8146(52) administered by the Transportation and Facilities Research Division, Agricultural Research Service, U.S. Department of Agriculture. The study was entitled "Investigations Designed to Determine the Extent and Causes of Physical Damage to Grain by Equipment Used in Handling Grain in Marketing Channels." Douglas E. Fiscus, research engineer, Cargill, Inc., conducted the studies under the supervision of Henry H. Kaufmann, manager, Grain Research Laboratory, Cargill, Inc., Minneapolis, Minn. The authors of this publication were responsible for the development and general direction of the research.

Results of this study were previously reported in part in Paper No. 69-853, entitled "Physical Damage of Grain Caused by Various Handling Techniques," and Paper No. 69-840, "Grain Stream Velocity Measurements Using High Speed Photography." Both were presented at the winter meeting of the American Society of Agricultural Engineers, Chicago, Ill. in December 1969. Both papers have been published in volume 14 of the Illinois "Transactions of the ASAE," Paper No. 69-840 on pages 162-166 and Paper No. 69-853 on pages 480-485, 491. The results of the handling studies with pea beans were reported at the Ninth Dry Bean Research Conference, Fort Collins, Colo., in August 1968, and were published in ARS 74-50 by the U.S. Department of Agriculture in January 1969.

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GRAIN BREAKAGE CAUSED BY COMMERCIAL HANDLING METHODS

By G. H. Foster, *research leader, North Central Region, Grain Marketing Research Center, Manhattan, Kans.*, and L. E. Holman, *formerly investigations leader,*[1] *Agricultural Research Service, United States Department of Agriculture*

SUMMARY

In determining the cause and extent of physical damage (breakage) to grain by commercial handling methods, 450 tests were made, most of which were replicated three and some four times. The total included 77 tests of dropping grain by free fall simulating bin filling and 50 tests of dropping grain through a spout simulating railcar filling. Also included in the total were 170 grain-thrower tests and 153 bucket elevator tests. There were 160 tests with corn, 155 with wheat, 125 with soybeans, and 10 with dry edible pea beans.

Results of the tests were measured in terms of the amount of grain breakage caused by each handling method. The breakage was determined by sieving and screening the grain after each test. The amount of grain in each test lot ranged from 30 to 230 bushels depending on the particular type of test. Since breakage from the entire test lot was removed and weighed, no sampling was involved.

The breakage caused by grain-handling methods was much greater and of more economic significance in corn than in soybeans or wheat. In some test replications, breakage in free fall from 100-foot heights ranged up to 14 percent with corn, 5.9 percent with soybeans, but less than 0.5 percent with wheat. In a single test with pea beans, breakage up to 13.6 percent in 100-foot free-fall was observed, although the pea beans were handled at moisture levels near 17 percent.

Drop height was the most significant test variable in the free-fall and spouting tests. The average breakage in corn ranged from 2.5 percent at a drop height of 40 feet to 10.2 percent at 100 feet. When impacting on a concrete surface inclined 45° to the grain stream, the corn breakage averaged 7.7 percent as compared with 6.0 percent when corn impacted on other corn. In the free-fall drop tests there was significantly more breakage in the stream from an 8-inch discharge than in a stream from a 12-inch discharge. With corn, the average breakage at all drop heights for 18 free-fall tests was 6.3 percent; for 12 spouting tests, it was 3.2 percent.

In the grain-thrower tests, the belt speed of the thrower was the most significant test variable affecting breakage. As belt speed was increased from 1,889 to 3,030 to 4,030 feet per minute, the average breakage in corn increased from 0.8 to 1.6 to 2.4 percent, respectively. The grain stream from the thrower impacted either a wood or steel bulkhead, with the wood bulkhead causing slightly less breakage.

In the bucket elevator tests, in which only the damage in the boot was measured, the two belt speeds used had no effect on the amount of breakage. A surprising result was that feeding the elevator on the back (down leg) resulted in slightly less breakage than feeding on the front (up leg). Apparently the breakage was caused by the impact between the grain and the bucket rather than from abrasion caused by dragging the grain through the boot.

One of the striking results of tests with all grains was the effect of repeated handling. The amount of breakage was cumulative and remained about constant each time the same lot of grain was handled or dropped. This was true regardless of whether or not the broken material was removed from the test lot before the second and subsequent handlings.

Of the two levels of corn moisture tested – about

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[1] Retired Jan. 1968.

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13 and 15 percent — there was consistently less breakage at the higher moisture level. There was also less breakage when the corn temperature was above 70° F. than when it was below 50°. In the corn tests a combination of lower moisture content and lower temperature resulted in five times more breakage than in tests with a combination of higher moisture and higher temperature.

High-speed photography was used to measure various grain streams and particle velocities.

The velocity of the grain streams in free-fall exceeded the terminal velocity of individual seeds falling in air. For example, the velocity attained by a stream from an 8-inch orifice equaled the terminal velocity of an individual soybean at 49 feet of free fall for soybeans. Grain breakage was closely related to the velocity attained at impact and mathematically was found to be an exponential function of grain stream velocity.

Grain velocities from the thrower almost equaled the velocities of grain streams in a free fall of 40 feet. Velocities from a bucket elevator almost equaled those of grain streams in a free fall of 10 feet.

INTRODUCTION

Grain often is broken or otherwise physically damaged during postharvest handling operations. Much of this breakage is attributed to the equipment and methods used in the repeated handling of grain as it moves through marketing channels. There is also evidence that grain characteristics, such as dryness and brittleness, and the drying method may affect the amount of breakage occurring during handling operations. Technological changes in grain production and harvesting, especially the recent shift to field shelling of corn, have added to the problem of grain breakage. Artificially dried field-shelled corn is brittle and easily broken. With repeated handling, breakage is often extensive enough to lower the market value of the corn.

Public attention has been attracted to the grain breakage problem because of increased grain exports and reputed charges that the United States exports grain of lower quality than some other exporting countries. Much of the alleged lower quality in exported corn is attributed to broken kernels.

Many opinions have been expressed concerning the extent of grain breakage caused by various handling methods, but little factual data have been available. If the grain industry is to reduce the amount of breakage caused by handling, it needs reliable information on the causes and extent of grain breakage in handling methods now in use.

Several researchers have investigated different aspects of the problem of physical damage to grain from mechanical causes. Byg and Hall (*4*),[2] Schmidt et al. (*18*), and Waelti and Buchele (*23*) determined corn kernel damage caused by the harvesting machine. Perry and Hall (*15*, *16*) reported the effect of drop height, bean moisture content, and impact velocities on pea bean damage. Clark et al. (*5*) and Kirk and McLeod (*13*) found relationships between impact velocity and cottonseed rupture. Bilanski (*2*) investigated the damage resistance of corn, soybeans, wheat, barley, and oats. Agness (*1*) investigated breakage, using laboratory devices for grain breakage tests. Sands and Hall (*17*) conducted laboratory tests to determine the amount of breakage to corn caused by screw conveyors operating at different screw speeds, flow rates, and inclinations.

These investigations either pertained to harvesting practices or were laboratory tests with single kernels or small quantities of grain. No work was reported concerning the grain damage that results from full-scale commercial handling methods.

Also, several researchers have published data on terminal velocity as well as other aerodynamic characteristics of grains. Such data are useful in the study of pneumatic conveying, threshing and cleaning operations, and related subjects. Hawk et al. (*9*) reported terminal velocities as well as other characteristics for various grains. Kiker and Ross (*12*) measured the velocity of lupine seeds in free fall. No work was reported relating to measured velocities of grain in streams of the dimensions encountered in commercial handling practices.

High-speed photography has been used to measure particle velocities. Brusewitz and Wolfe (*3*)

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[2] Italic numbers in parentheses refer to Literature Cited, p. 19.

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and Collins et al. (*6*) used it to measure the velocity of forage in a pneumatic conveying system and Kiker and Ross (*12*) to measure the velocity of lupine seed. Hyzer (*10*) described a wide range of engineering studies in various industries that used high-speed photography.

TEST PROGRAM AND OBJECTIVES

The objectives of the research were to investigate the cause and extent of physical damage (breakage) to various grains by different commercial handling methods and to provide data that will point to remedial and corrective measures for minimizing grain breakage.

Full-scale grain-handling equipment of commercial sizes and capacities was used in the study. The entire quantity of grain in each test was analyzed to determine the amount of breakage in each handling method studied. This eliminated sampling errors that occur when small samples are obtained from sizable grain lots.

Grains Tested

The five grains[3] used in the tests were yellow corn, yellow soybeans, hard red spring wheat, hard red winter wheat, and dry edible pea beans.

The range in moisture content and temperature of the grains tested are listed in table 1.

All test grains, except pea beans, were obtained from commercial marketing channels in Minneapolis, Minn. Pea beans, classed as "Michigan Choice Hand Picked Beans" (*20*), were shipped from Saginaw, Mich., to Minneapolis in 100-pound bags. Corn was obtained at 17- to 22-percent moisture content and artificially dried to the desired lower moisture level. A continuous-flow grain dryer was used in which corn temperatures were not allowed to exceed 140° F. Soybeans, wheat, and pea beans were not artificially dried. All test grains were judged to have physical properties typical of grains in commercial trade.

Some of the physical properties of the corn from the 1967 crop (one of two test lots used) were evaluated. From 30 to 40 percent of the kernels showed mechanical damage from harvesting or handling prior to the tests. Eighty to eighty-five percent of the kernels had stress cracks from rapid drying or machine harvesting or both. This compares with an average of about 90 percent of the kernels with stress cracks in corn dried with heated air in 62 tests with continuous-flow and batch dryers (*7*). The breakage in the corn from the

TABLE 1.—*Grain test variables and minimum test weights*

Grain	Grain test variables				Minimum test weight
	Moisture content		Temperature		
	Low	High	Low[1]	High[2]	
	Percent	*Percent*	*° F.*	*° F.*	*Pounds per bushel*
Corn	12.6-13.3	14.8-15.4	25-43	76-85	53
Soybeans	10.7-11.1	12.5-12.6	32-46	58-61	54
Spring wheat . . .	10.9-11.1	12.9	34-47	77-82	57
Winter wheat . .	10.9-11.4	None	27-45	82-83	58
Pea beans	15.5	16.9-17.2	(3)	(3)	57

[1] Test limit — 50° F. maximum.

[2] Test limit — 75° F. minimum except for soybeans.

[3] Grain temperature was not a variable in pea bean tests but ranged from 47° to 63° F.

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[3] The term "grain" as used in this report includes all crops tested.

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1967 crop, as determined by a sample breakage tester, was about 18 percent, somewhat higher than the 11 percent in the corn from drying tests mentioned previously. Therefore, the physical properties of the corn were typical of those of corn that had been mechanically harvested and artificially dried with heated air.

The test lots of grain were precleaned with commercial grain cleaners to remove weed seeds, chaff, straw, and other extraneous material. This grain was next passed over vibrating wire mesh screen No. 1 (fig. 1) to remove all small broken kernels prior to testing. This screen had openings slightly larger than those listed below for screen No. 2 to assure that the test lot would not initially contain any material that would be counted in the "breakage."

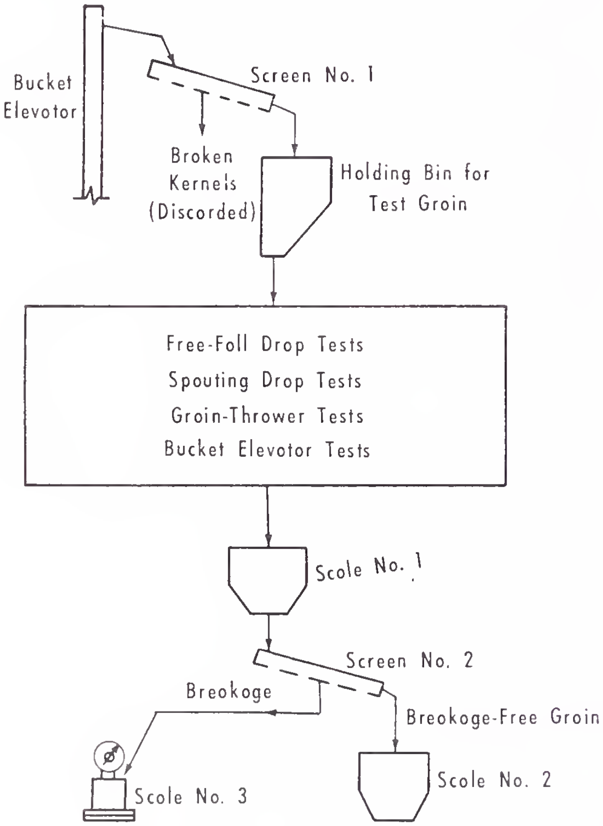

FIGURE 1.—Grain-flow diagram for handling tests.

After testing, vibrating screen No. 2 was used to remove the breakage from the entire test lot of 30 to 230 bushels of grain. The commercial wire mesh screens used approximated the sieve sizes prescribed in the grading standards of the U.S. Department of Agriculture (*21*). No 2 screen sizes were as follows:

Grain	*Screen opening (inches)*	*Screen wire diameter (inches)*
Corn	0.159 (square)	0.041
Soybeans ..	0.158 by 0.5 (rectangle)	.072
Wheat	0.065 by 0.25 (rectangle)	.035

The weight of broken material separated by screen No. 2, taken as a percentage of the total weight of the grain test lot, is reported as the breakage in this study.

Handling Methods and Equipment Tested

The handling methods and equipment tested were dropping of grain, both in free fall and through spouting, grain thrower, and bucket elevator. Handling methods were varied in regard to drop heights, discharge openings, impact surfaces, types of spout ends, belt speeds, types of and loading of elevator buckets, and methods of feeding bucket elevators.

The variables studied in the grain-drop, thrower, and bucket elevator tests are listed in appendix tables 17, 18, and 19.

The free-fall tests simulated dropping grain into a storage bin from heights of 40, 70, and 100 feet using 8- and 12-inch diameter discharge orifices. The grain stream at discharge was approximately the same size as the orifice. In one test series the grain impacted a concrete slab at an angle of 45° to simulate dropping into a hopper-bottom bin. In other tests, grain impacted on grain in a cylindrical container to simulate dropping into a partially filled bin. Figure 2 shows the slab and the cylinder.

In the spouting tests simulating railcar loading, a 90° elbow was installed at the spout end to dis-

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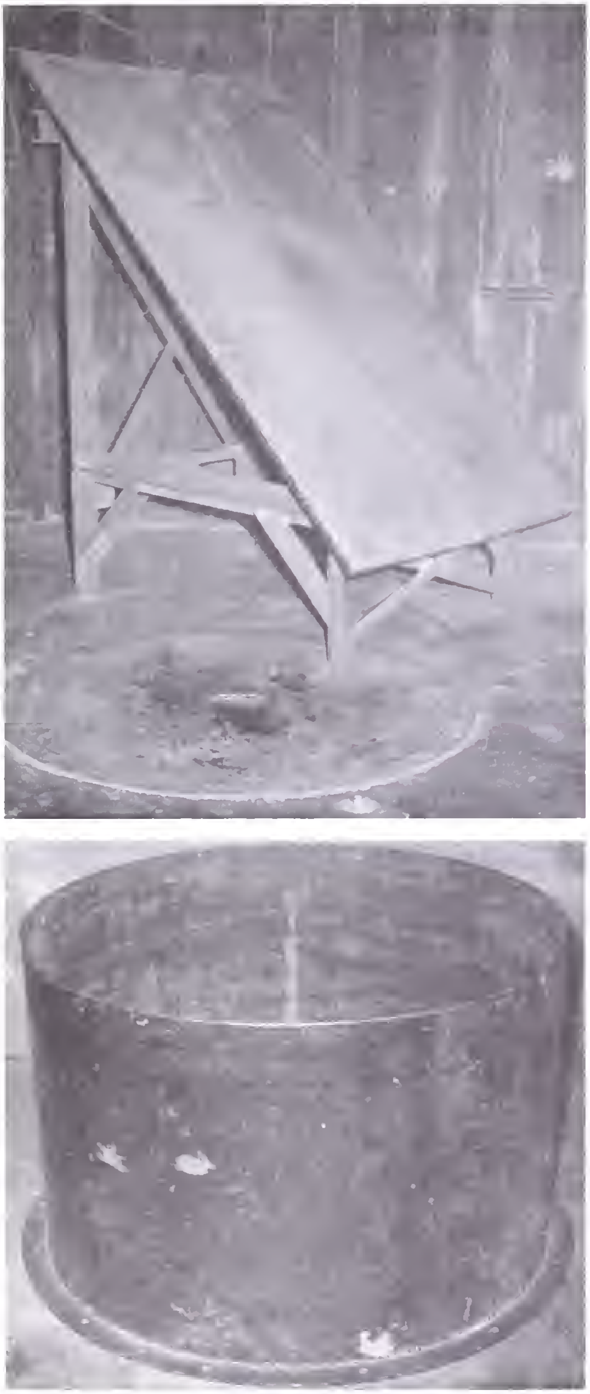

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Figure 2.—Inclined concrete slab and metal grain container used in free-fall grain drop tests.

charge grain horizontally against a steel surface 20 feet from the centerline of the vertical spout. Figure 3 shows two of the three spout ends tested. Drop heights of 40 and 100 feet were used. During ship loading, grain throwers are often attached to the loading spout end by a bar through the spout. A ¾- by 2-inch steel bar was used in the flexible turn spout end to simulate the attachment of a grain thrower.

For both free-fall and spouting drops, the lower edge of the discharge orifice was designated as the 0-foot drop distance. Figure 4 illustrates the setup for both free-fall and spouting drop tests.

The grain-thrower (trimmer or slinger) tests simulated the use of such equipment for loading railcars, barges, and ship holds. Figure 5 shows the setup for the thrower tests.

A conventional bucket elevator with 9- by 6-inch buckets spaced 8 inches apart on a 12-inch wide belt was used for the tests. The head pulley was 5 feet in diameter and the tail pulley 2½ feet. Elevator belt speeds of 650 and 940 feet per minute (f.p.m.) were tested. The head cover of the elevator was removed allowing unrestricted discharge from the buckets. Thus, the tests determined only the grain breakage in the elevator boot that was related to back and front feeding, to full and half-full bucket loading, and to type of bucket used. Figure 6 shows the test installation.

Grain Stream Velocities

Grain stream velocities produced by the handling methods and equipment tested were measured by high-speed photography. These measurements were made to study the relationship between impact velocity and grain breakage. Stream velocities were determined for yellow corn, yellow soybeans, and hard winter wheat in free-fall drop and when handled by a grain thrower. The velocity of the grain discharging from the head of the bucket elevator also was measured, but this was not directly related to the damage produced in the boot.

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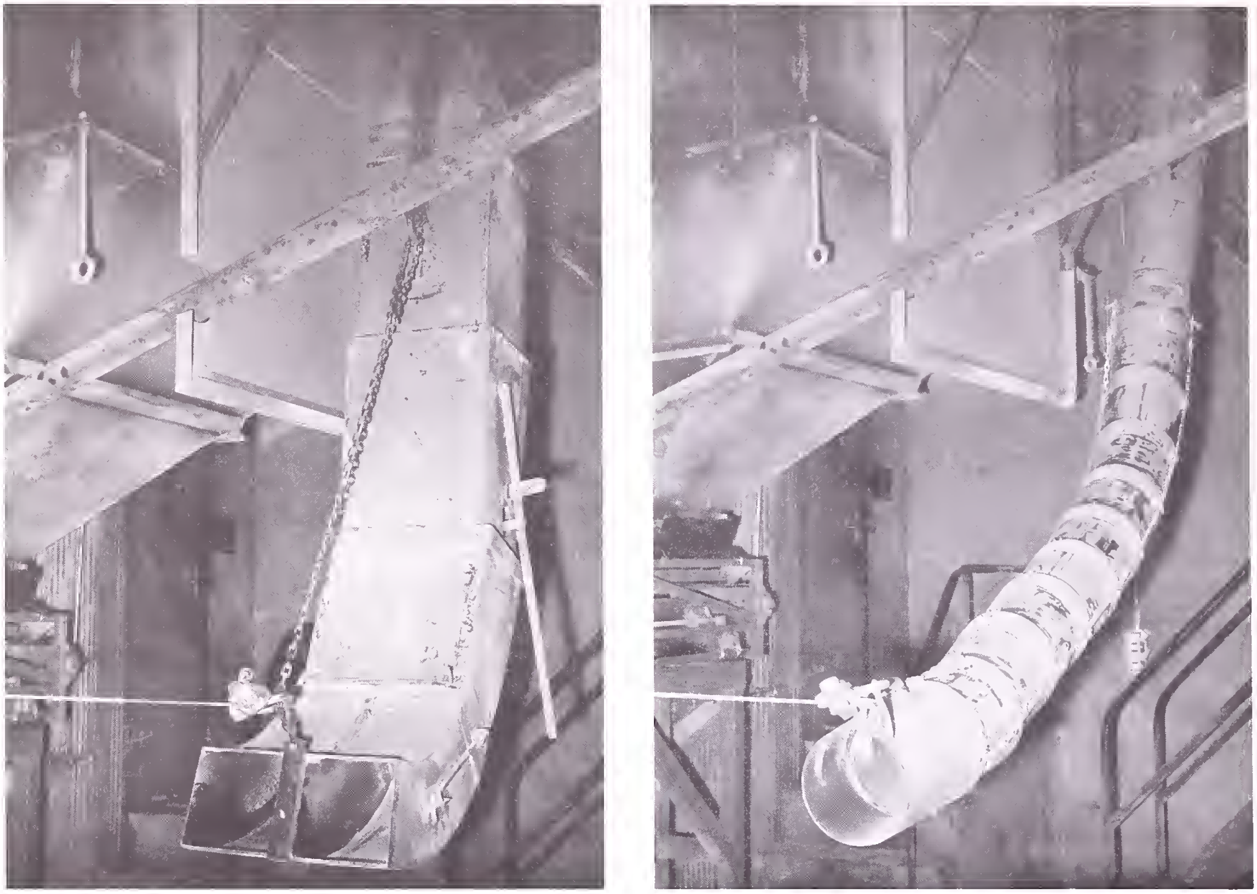

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FIGURE 3.—Two types of spout ends used in spouting tests: *Left,* bifurcated; right, flexible turn. Bifurcated spout ends were rotated 90° from their normal position to accommodate the test space available.

ANALYSIS PROCEDURE

In the breakage tests the dependent variable was grain breakage and the independent variables were handling method and grain type and condition. Each test was replicated at least three times and the average breakage for each test condition calculated.

In the velocity tests the measurements were repeated either nine or 10 times because of variation in the grain velocities observed.

The test data were analyzed statistically by analysis of variance (*8*) to determine which of the test variables significantly affected the results. Significant differences between the grain breakage averages and between grain velocity averages, where there were more than two levels of a variable, were determined by the Q-test (Snedecor and Cochran *19*) or the D-test (Neter and Wasserman *14*).

GENERAL BREAKAGE RESULTS

Table 2 shows the relative average amount of breakage that occurred in three different grains with the four handling methods tested. Appendix tables 17, 18, and 19 give the results for all the

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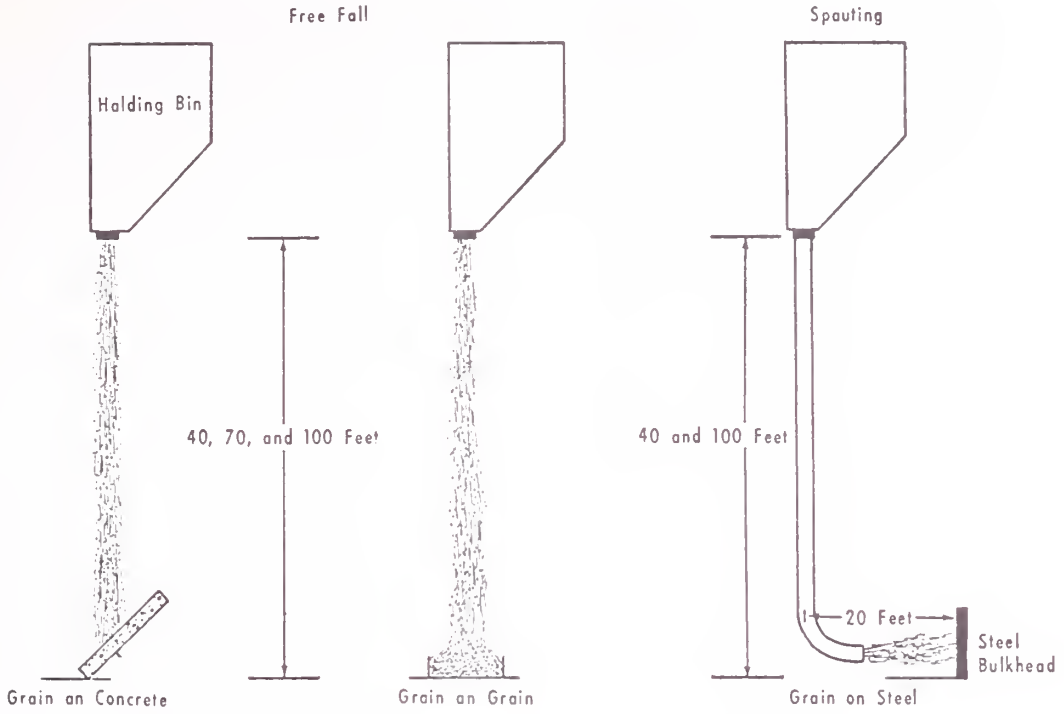

FIGURE 4.—Grain-flow diagram for free-fall and spouting drop tests.

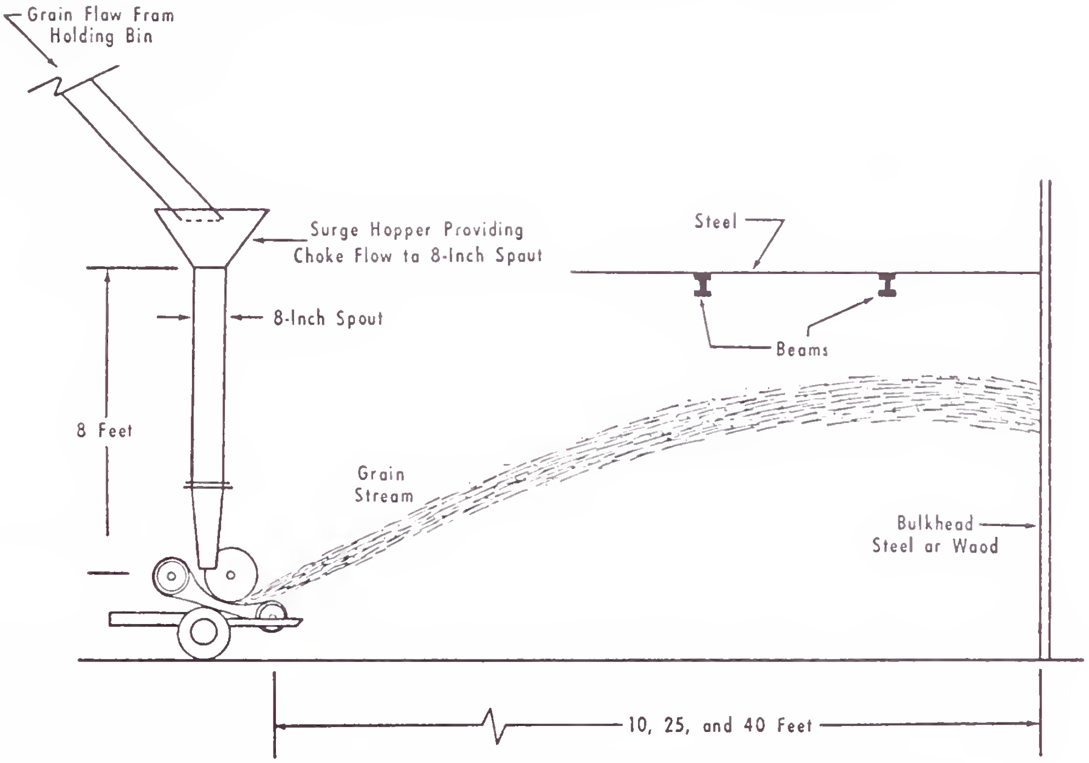

FIGURE 5.—Grain thrower and bulkhead arrangement used in thrower tests.

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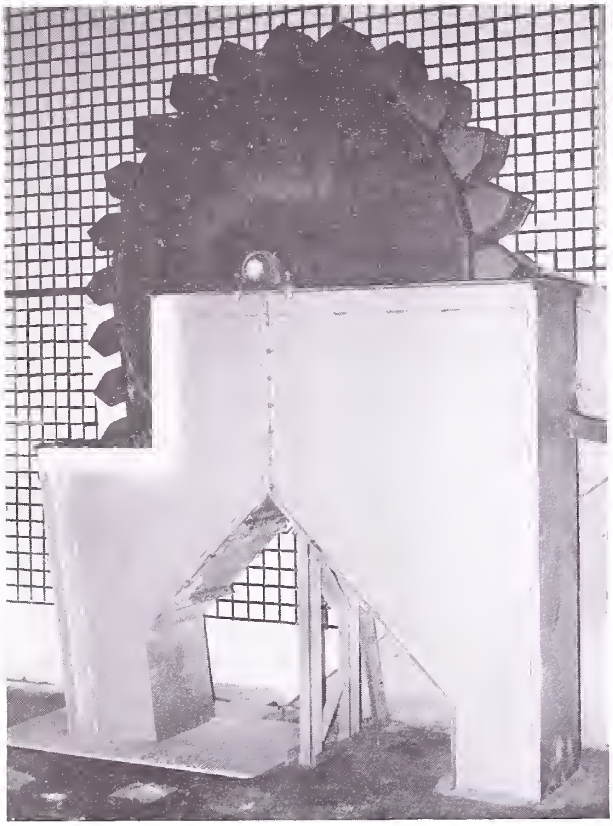

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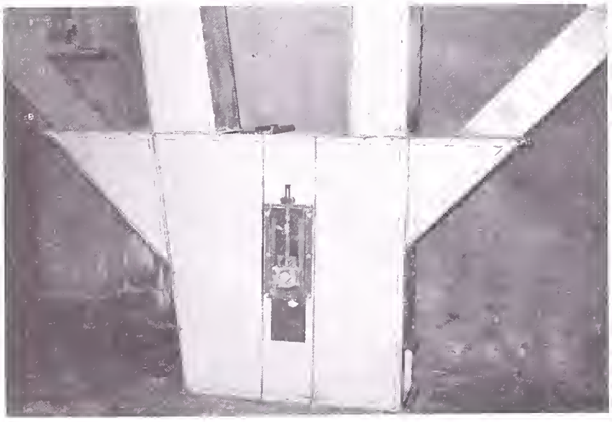

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FIGURE 6.—Head and boot sections of bucket elevator used in tests: *Top*, head without cover; *bottom*, boot with front and back feed.

TABLE 2.—*Relative amounts of breakage with 3 grains and 4 handling methods.*[1]

Grain	Breakage caused by —			
	Free-fall drop	Spouting drop	Grain thrower	Bucket elevator
	Percent	*Percent*	*Percent*	*Percent*
Corn	6.3	3.2	1.6	1.1
Soybeans ..	2.0	1.0	.7	.3
Wheat	.2	.15	.2	.1

[1] Average of all test conditions for each handling method for each grain.

different test conditions and grains tested, except the 26 special tests conducted to study repeated handling of the same grain.

For each type of grain the free-fall drop caused the greatest average breakage and the bucket elevator the least. The differences in breakage between drop, thrower, and bucket elevator tests were greatest for corn and least for wheat.

Corn had the highest breakage. Its broken particles ranged in size from dust to the largest particles that would pass the screen opening. As compared with wheat, corn has a structurally weak kernel that tends to break into random size particles.

The breakage in soybeans and pea beans was practically all splits, where the kernel broke in half. Unlike corn and wheat, soybeans and pea beans have two structurally strong halves held together by a weak bond.

Wheat breakage was so low that no significant differences in breakage occurred in spring or winter wheats for any handling method tested. Wheat is structurally strong compared with corn, soybeans, and pea beans, and any breakage in wheat appears to be caused by abrasion rather than by impact.

In this report the corn breakage results are discussed in considerable detail and soybean breakage in less detail. Because wheat breakage was so low in all tests, the results are only briefly summarized. Since the pea bean results have been published (*22*), they are also discussed only briefly here.

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CORN BREAKAGE

There were 160 handling tests conducted with corn. In 58 of these tests the breakage produced was enough to lower the market grade. In some tests the damage level exceeded the limit for any of the numerical grades, and the corn after handling was U.S. sample grade. Nearly all the breakage measured in these tests would be included in "broken corn and foreign material" as a grading factor in U.S. official grade standards for corn. Thus the corn breakage measured is of direct economic importance.

Drop Tests

The handling treatment that caused the most breakage was the free-fall drop on a 45° inclined concrete surface. This test simulated conditions at the start of filling a concrete bin with a hopper bottom. At a 100-foot drop height a maximum of 14 percent breakage was recorded.

All the variables in the free-fall drop tests, including drop height, impact surface, and orifice (stream) size, significantly affected the amount of breakage. The data from these tests are summarized in table 3.

Breakage was affected most by drop height and increased rapidly at heights greater than 40 feet.

Breakage caused by corn falling on other corn was slightly less than that caused by corn falling on concrete. The lower breakage rate for corn on corn was observed at all drop heights and all grain temperatures and moistures tested, indicating that grain is a more elastic impact surface than concrete (see appendix table 17).

Table 3 also shows that the corn stream from the 8-inch orifice had consistently greater breakage than that from the 12-inch orifice, averaging 2.3 percentage points greater. It is theorized that the corn stream with the larger diameter had a more cushioning effect on impact because of its larger mass. There also appeared to be more kernel interaction and less stream dispersion, which resulted in more corn on corn impact and less individual kernel impact on concrete. However, tests of a greater variety of stream sizes are needed to substantiate this theory.

Dropping corn through spouting with a 90° turn on the spout end and impacting it against a vertical steel bulkhead caused about half the breakage as compared with the results in the free-fall tests at the same drop heights (tables 3 and 4). Both the bifurcated spout end and the spout end with flexible turn and bar had a metal projection in the middle of the spout end, causing part of the dropping corn to impact on steel. These two spout ends caused more corn breakage than the spout end with no bar.

The lower grain breakage levels in spouting as compared with breakage in free fall were probably not related to velocity. Although the grain velocity was not measured in the spouting tests, the grain flow from an 8-inch orifice was much greater in spouting than in free fall. The differences for corn were as follows:

Drop height (feet)	*Grain flow rate (pounds per minute)*	
	Free fall	*Spouting*
100	2,866	5,606
40	2,481	4,221

These data show a 70- and 96-percent increase in corn flow in spouting as compared to free fall at 40- and 100-foot drop heights. Similar increases were measured in the soybean tests, but the increases in the wheat tests were only about half those with corn.

The lower breakage in the spouting tests as compared with breakage in the free-fall tests may be due in part to the greater flow and for the same reasons that there was less breakage in the larger free-fall streams. The grain stream being confined in the spouting, the 90° turn on the spout end, and the horizontal discharge against a vertical bulkhead also may have contributed to the lower breakage in the spouting tests.

Grain-Thrower Tests

The average breakage from handling corn with a grain thrower was about equal to that for a 40-foot drop through spouting (tables 4 and 5). Of the variables tested, thrower belt speed had the largest effect on breakage and the breakage was almost linear with belt speed.

The use of vertical wood or vertical or horizontal steel bulkheads caused no significant difference in breakage in the corn-thrower tests. The breakage

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TABLE 3.—*Corn breakage in free-fall drop tests*[1]

Test condition	Breakage Average	Breakage Range
	Percent	*Percent*
Drop height (feet):		
100	10.2	6.9-14.0
70	6.2	2.3- 7.9
40	2.5	.2- 5.9
Impact surface:		
Concrete—45°	7.7	.8-14.0
Grain—90°	6.0	.2-12.7
Discharge stream size (inches):		
8	7.7	.9-14.0
12	5.4	.2-13.6

[1] 6 tests for each test condition.

TABLE 4.—*Corn breakage in spouting tests*[1]

Test condition	Tests	Breakage Average	Breakage Range
	Number	*Percent*	*Percent*
Drop height (feet):			
100	6	5.0	1.5-8.3
40	6	1.5	.2-3.0
Spout end:			
Bifurcated	4	3.4	.3-8.3
Flexible turn	4	2.8	.3-7.0
Flexible turn with bar	4	3.5	.3-8.0

[1] Impact against steel bulkhead at 20-foot distance.

with the bulkhead at 10 feet was slightly higher than at 25 and 40 feet. The corn stream had a curved trajectory and hit the bulkhead less squarely at 25 and 40 feet than at 10 feet.

TABLE 5.—*Corn breakage in grain-thrower tests*

Test condition	Tests	Breakage Average	Breakage Range
	Number	*Percent*	*Percent*
Belt speed (f.p.m.):			
4,030	12	2.4	0.5-5.6
3,030	12	1.6	.5-2.9
1,889	12	.8	.3-2.0
Bulkhead type:			
Wood vertical	20	1.5	.3-5.5
Steel vertical	20	1.7	.3-5.6
Steel horizontal	19	1.7	.3-4.9
Bulkhead distance (feet):			
10	12	2.4	.3-5.6
25	12	1.6	.5-3.6
40	12	1.6	.5-3.7

Bucket Elevator Tests

The breakage in the bucket elevator tests was confined to that in the boot of the elevator since the elevator head cover was removed, the discharge was unrestricted, and the grain leaving the buckets fell to the floor only 6 feet below the center of the head pulley. The corn breakage in the elevator tests averaged only a little over 1 percent with a maximum of 3.5 percent (table 6). There was no difference in the breakage of corn at the two elevator belt speeds tested, a result not expected. Half-full buckets caused an average breakage of 0.2 percent over that with full buckets. Presumably this slightly higher breakage was caused by a larger percentage of the kernels impacting on the unfilled part of the steel buckets. After the bucket is partially full, more of the filling impact is grain on grain.

Feeding the elevator on the back (down leg) averaged 0.2 percent less breakage than feeding on the front (up leg). This difference is small but statistically significant. With front feeding, the falling grain first impacts empty buckets traveling upward. With back feeding both the empty bucket and the grain travel downward and the bucket fills as it moves around the tail pulley. Since the relative velocity between corn and bucket was less in back feeding, the impact force and corn breakage were less.

TABLE 6.—*Corn breakage in bucket elevator tests*[1]

Test condition	Breakage Average	Breakage Range
	Percent	*Percent*
Belt speed (f.p.m.):		
650	1.1	0.2-3.5
940	1.1	.3-3.4
Bucket loading:		
Full	1.0	.2-3.5
Half full	1.2	.2-3.4
Feeding method:		
Front (up leg)	1.2	.2-3.5
Back (down leg)	1.0	.2-3.4
Bucket type:		
Nu-hy	1.1	.2-3.5
Link belt	1.1	.2-3.4

[1] 32 tests for each test condition.

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Effect of Repeated Handling on Corn Breakage

In commercial practices, grain is often handled several times, and the breakage is allowed to accumulate from successive handlings. Although breakage-free grain was used in most of these tests, a few tests were repeated without the breakage removed to study the effect of repeated handling.

Table 7 shows the amount of breakage produced by the repeated handling of corn with a grain thrower as compared with that when a new breakage-free lot was used each time. The amount of breakage was about the same each time the corn was handled (test replication) regardless of whether new corn was used each time, the same corn was used with the breakage removed after each handling, or the same corn was used and the breakage allowed to accumulate. The cumulative breakage from four handlings with the grain thrower was 24.7 percent when the broken kernels were retained after each handling and 21.0 percent when the broken kernels were removed after each handling.

TABLE 7.—*Effect of repeated handling on corn breakage in grain-thrower tests*[1]

Test replication (No.)	New corn each replication		Same corn each replication with—			
			Breakage *removed* after each replication		Breakage *retained* after each replication	
	Breakage each replication	Cumulative breakage	Breakage each replication	Cumulative breakage	Breakage each replication	Cumulative breakage
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	5.3	——	5.1	——	5.3	——
2	5.5	10.8	5.8	10.9	6.8	12.1
3	5.2	16.0	5.4	16.3	6.9	19.0
4	—	——	4.7	21.0	5.7	24.7

[1] Belt speed 4,030 f.p.m., wood bulkhead 10 feet from thrower, and corn with 13.2-percent moisture at 49° F.

The breakage in the tests with other handling methods was cumulative with repeated handling, but the results were more variable.

Effect of Corn Moisture and Temperature on Breakage

An important part of this study was to determine how the condition of the grain, in terms of its temperature and moisture content, affected the amount of breakage. The data in table 8 show the effect of both moisture and temperature on corn breakage. With the thrower, for example, there was an average breakage of 2.4 and 0.8 percent, respectively, in tests with 13- and 15.2-percent moisture corn. A decrease of only a little over 2 percent in the moisture level at which the corn was handled resulted in a threefold increase in breakage.

The effect of corn temperature on breakage was somewhat less than the moisture effect. Handling the corn at near 80° F. rather than at near 40° reduced the breakage nearly 50 percent (table 8).

TABLE 8.—*Effect of moisture content and temperature on corn breakage*

Grain variable and tests	Tests	Breakage	
		Average	Range
	Number	*Percent*	*Percent*
Moisture content (percent)			
Drop tests:			
12.6	15	7.3	2.4-14.0
15.2	15	2.9	.1- 9.8
Thrower tests:			
13.0	29	2.4	.6- 5.6
15.2	30	.8	.3- 1.9
Bucket elevator tests:			
13.0	32	1.7	.6- 3.5
15.0	32	.5	.2- 1.5
Temperature (F.)			
Thrower tests:			
41°	30	2.0	.4- 5.6
77°	29	1.2	.3- 2.8
Bucket elevator tests:			
36°	32	1.6	.2- 3.5
84°	32	.6	.2- 1.5

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When the effect of both moisture and temperature are taken together, the breakage in low moisture-low temperature corn was five times more than that in high moisture-high temperature corn. Thus to minimize breakage, corn should be handled at the highest practical moisture content and temperature. However, these grain conditions are totally opposite to those recommended as good storage practices.

SOYBEAN BREAKAGE

In the 125 tests conducted with soybeans the breakage was approximately one-third that in corn. Nearly 95 percent of the breakage was splits (beans split in half) and 5 percent was broken pieces of beans that would be included in "foreign material" in the U.S. grade standards for soybeans. Neither the amount of splits nor the "foreign material" produced in any single handling test exceeded the limits for U.S. No. 1 grade soybeans. Only in the repeated handling tests in which the breakage accumulated were the damage levels high enough to affect the market grade and be of direct economic importance.

Drop Tests

Dropping soybeans in free fall was the handling treatment that caused the most breakage. The average breakage in the free-fall and in the spouting tests was as follows:

Drop height (feet)	*Free fall (percent)*	*Spouting (percent)*
100	3.5	1.4
70	1.6	–
40	.8	.6

As with corn, soybeans in free fall had significantly greater breakage from an 8-inch than from a 12-inch diameter orifice, averaging about 1 percent greater. Breakage caused by soybeans falling on other soybeans was consistently less than when falling on concrete, as shown in table 9.

TABLE 9.—*Comparison of breakage in soybeans dropped on concrete and on other soybeans*

Drop height (feet)	Breakage of soybeans on— Concrete	Breakage of soybeans on— Soybeans
	Percent	*Percent*
100	4.5	3.2
70	2.1	1.4
40	1.1	.7
Average	2.6	1.8

In the spouting tests the average soybean breakage with the three different spout ends is given in table 10. As with corn, the metal projection in the ends of two of the spouts caused some of the dropping soybeans to impact on steel. This impact caused higher breakages but not so much as in the corn tests.

TABLE 10.—*Effect of type of spout end on soybean breakage in spouting tests*

Drop height (feet)	Average breakage by type of spout end: Bifurcated	Flexible turn	Flexible turn with bar
	Percent	*Percent*	*Percent*
100	1.3	1.1	1.7
40	.5	.5	.7
Average	.9	.8	1.2

Grain-Thrower and Bucket Elevator Tests

At the highest belt speed tested (4,030 f.p.m.) the soybean breakage did not exceed 1.6 percent at bulkhead distances of 10, 25, and 40 feet.

The breakage for any elevator test run did not exceed 0.7 percent.

Results of each handling test with soybeans are given in appendix tables 17, 18, and 19.

Effect of Repeated Handling on Soybean Breakage

A few conditions were selected to test the effect of repeated handling on soybean breakage. Table 11 shows the effect of repeated handling on breakage when the same soybeans were dropped four times from 100 feet onto concrete. The breakage was removed and weighed after each test replication. The breakage for soybeans at 12.6-percent moisture content and 50° F. was about the same for each handling. Breakage decreased for each

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TABLE 11.—*Effect of repeated handling on soybean breakage using same soybeans for each test replication*[1]

Test condition		Breakage produced in replication —				
Moisture (percent)	Temperature (° F.)	1	2	3	4	Cumulative breakage
		Percent	*Percent*	*Percent*	*Percent*	*Percent*
10.7	46	3.2	3.0	2.5	2.0	10.7
11.0	32	4.0	2.5	2.0	1.6	10.1
12.6	50	1.4	1.2	1.4	1.2	5.2

[1] 100-foot free-fall drop onto concrete. Breakage removed after each replication.

replication at the two lower moisture and temperature levels.

Effect of Soybean Moisture and Temperature on Breakage

The effect of moisture content and temperature on the breakage of soybeans and corn was similar. In free-fall drop the breakage in soybeans at 10.7-percent moisture averaged 2.3 percent but was only 0.89 percent in 12.6-percent moisture beans. In the thrower tests the moisture difference between the two lots was 1.4 percent, and the lower moisture beans had 0.5 percent more breakage. These breakage differences relating to moisture content were statistically significant.

The temperature difference in the two lots of beans of similar moisture content was only 14° F. in the drop tests and 22° in the thrower tests. The warmer beans showed less breakage in both tests, but the difference was statistically significant only in the thrower tests.

WHEAT BREAKAGE

Wheat breakage was so low that there was no significant breakage related to wheat class, moisture content, and temperature or to any of the handling methods tested. The amount of breakage produced by any test with wheat did not exceed 1 percent even in four repeated handlings. Appendix tables 17, 18, and 19 give the results of the wheat breakage studies.

PEA BEAN BREAKAGE

Breakage of pea beans, as measured in limited tests, was greater than breakage of soybeans and wheat and was approximately the same as that of corn. For example, in the one test where pea beans were dropped 100 feet (free fall) onto a concrete surface, the breakage (splits) amounted to 13.6 percent. Since the pea bean studies have been published by the Department (22), the results are not discussed here, but individual test data are included in appendix tables 17 and 19.

GRAIN VELOCITIES IN HANDLING METHODS TESTED

Grain velocity was measured to determine relationships between impact velocity and grain breakage. A high-speed motion picture camera (fig. 7) was used to photograph the various grain streams. Film speeds of 2,000 to 7,000 frames per second were used.

Free-fall velocities were the highest of those measured. Discharge velocities in the elevator tests were lowest and equivalent to free-fall velocities at about 10 feet; those in the thrower tests were equivalent to free-fall velocities at about 40 feet. In thrower tests the grain velocities were lower

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FIGURE 7.—Setup for high-speed photographic study of velocity of grain streams in free fall.

than the belt speed because of slippage between belt and grain. Conversely, in the elevator tests the grain velocities were higher than the belt speed since the grain must travel faster than the belt in order to leave the buckets.

Free-Fall Velocities

The free-fall velocities of soybeans averaged 6 percent greater than those for corn or wheat. Table 12 shows free-fall velocities as high as 4,140 f.p.m. for soybeans at a drop height of 85 feet. This table shows the relationship between free-fall velocity and drop height.

The velocity of the grain stream from a 12-inch orifice averaged 6 percent higher than that from an 8-inch orifice. The orifice size had little effect on velocities at drop heights of less than 40 feet. Between 41 and 85 feet the stream from the 8-inch orifice dispersed more and became less dense than the stream from the 12-inch orifice. Therefore a higher percentage of the kernels in the 8-inch stream were subjected to air resistance, resulting in lower velocities.

The velocity of grain falling in a stream for 50 or more feet exceeded the single kernel velocity but was less than the theoretical free-fall velocity (fig. 8). A single kernel is limited in velocity because of air resistance. However, a stream of grain acts as a mass and not all the individual kernels are equally affected by aerodynamic drag. The stream velocities shown were determined by the equation given in figure 8, and the curves are a least square fit of observed velocities for all grains tested. The intercept, or velocity at zero feet,

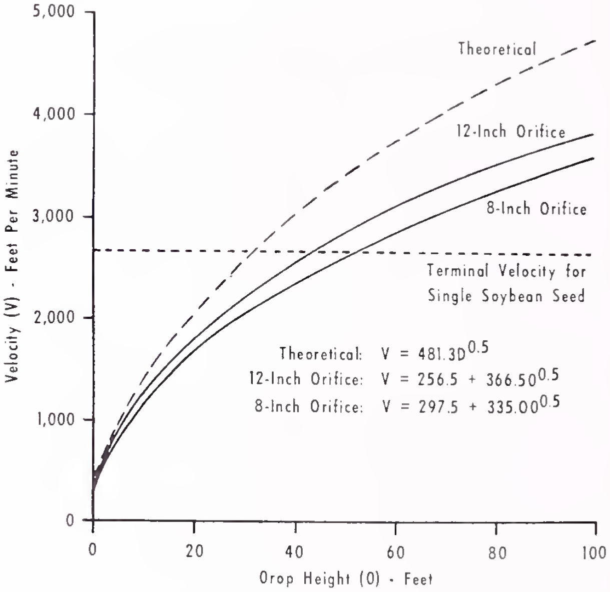

FIGURE 8.—Free-fall grain stream velocities, as predicted by equations shown, compared to individual seed terminal velocity for soybeans.

TABLE 12.—*Velocities of grain streams in free fall*

Grain	Orifice diameter	Mean grain stream velocity for indicated drop heights (feet)				
		0	10	41	69	85
	Inches	*F.p.m.*	*F.p.m.*	*F.p.m.*	*F.p.m.*	*F.p.m.*
Corn	8	360	1,280	2,350	2,835	3,410
	12	400	1,355	2,230	3,030	4,000
Soybeans	8	355	1,320	2,410	3,260	3,630
	12	395	1,320	2,505	3,260	4,140
Wheat	8	340	1,320	2,390	3,210	3,260
	12	370	1,385	2,440	2,790	4,000

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represents the grain movement in the holding bin as it flows toward the discharge.

Patterns of corn streams in free fall from both 8- and 12-inch orifices are illustrated in figure 9. Patterns of soybean and wheat streams were similar to those of corn.

Grain-Thrower Stream Velocities

The velocity of the grain stream from a grain thrower increased with increasing thrower belt speed, but it was less than that of the belt because of slippage between the belt and the grain. Table 13 shows the amount of slippage occurring with corn, soybeans, and wheat with three thrower belt speeds. As indicated in this table, increasing belt speed did not produce a proportional increase in grain velocity. Because of the increasing grain slippage, there appears to be little advantage in operating thrower belts faster than about 4,000 f.p.m.

There were no significant differences between grain stream velocities at thrower distances of 0, 20, and 25 feet, but at 10 feet the velocities were significantly lower. As the grain left the thrower the stream was moving upward at angles of 12° to 14° from the horizontal. At a distance of 10 feet the stream was nearly horizontal and had slowed down. At 20 and 25 feet the grain stream was moving downward again and had accelerated to near its initial velocity.

Discharge Velocities From Elevator Buckets

In the bucket elevator tests the velocity was measured as the grain discharged from the buckets

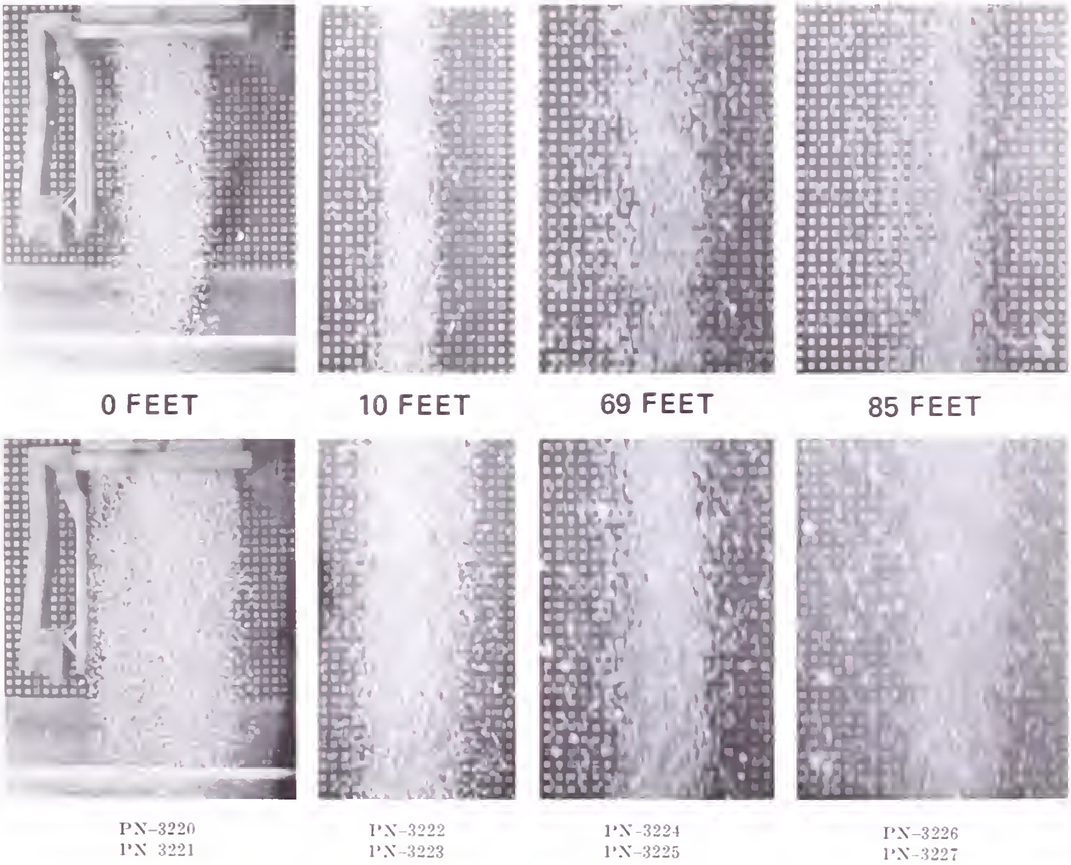

FIGURE 9.—Patterns of corn streams in free fall from 8-inch (above) and 12-inch (below) orifices at four heights. Higher grain velocities are apparent as the drop height increases; also, stream size decreases with some dispersion and breaking up of the stream.

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TABLE 13.—*Grain-thrower stream velocities and amount of grain slippage at 3 thrower belt speeds*

Grain	Thrower belt speed[1]	Mean grain velocity	Difference between grain and belt velocity	Slippage of grain on belt
	F.p.m.	*F.p.m.*	*F.p.m.*	*Percent*
Corn	3,810	2,210	1,600	42.0
	2,880	2,140	740	25.7
	1,800	1,580	220	12.2
Soybeans	3,810	2,415	1,395	36.6
	2,880	2,185	695	24.1
	1,800	1,595	205	11.4
Wheat	3,810	2,755	1,055	27.7
	2,880	2,360	520	18.1
	1,800	1,650	150	8.3

[1] Measured under load; no load belt speeds were 4,030, 3,030, and 1,889 f.p.m.

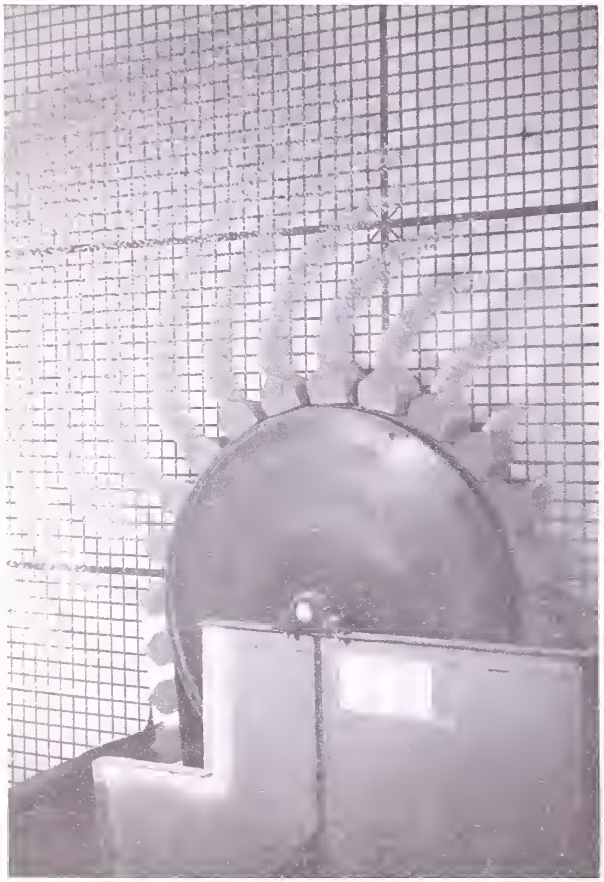

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FIGURE 10.—Patterns of corn leaving bucket elevator at belt speed of 940 feet per minute.

(head cover removed). Patterns and trajectories for corn leaving the buckets are shown in figure 10.

Grain velocities must be greater than the elevator belt speed for grain to discharge from the bucket. The relationship between bucket tip speed and grain velocity is as follows:

Bucket tip speed (f.p.m.)	*Grain velocity (f.p.m.)*
790	950
1,145	1,290

Data were averaged for corn, soybeans, and wheat.

Relationship Between Grain Velocity and Breakage

The relationship between grain stream velocity and breakage for corn and soybeans for free-fall and grain-thrower tests is shown in tables 14 and 15, respectively. It is obvious from these data that higher moisture grain can tolerate higher impact velocities than lower moisture grain. For example, a free-fall velocity of 3,125 f.p.m. caused slightly less damage to 15.2-percent moisture corn than a velocity of 2,420 f.p.m. to 12.6-percent moisture corn. Similar relationships are evident in the data for the thrower tests and for soybeans as well as corn.

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Breakage was found to be an exponential function of velocity in the form

$$B = cV^n$$

where

B is percent breakage.

V is velocity in f.p.m.

c and n are constants related to kind of grain, its moisture content and temperature.

The breakage data from the tests for each type of grain were subjected to regression analysis and the best fit equations were derived. Separate constants were determined for the two moisture levels in the corn and soybean tests. The resulting equations are as follows:

Corn (13-percent moisture)

$$B = 6.5 \times 10^{-10} V^{2.9}$$

Corn (15-percent moisture)

$$B = 6.3 \times 10^{-10} V^{2.8}$$

Soybeans (11.0-percent moisture)

$$B = 7.5 \times 10^{-8} V^{2.2}$$

Soybeans (12.5-percent moisture)

$$\mathrm{B} = 7.2 \times 10^{-7} V^{1.5}$$

TABLE 14.—*Effect of grain stream velocity on breakage in free-fall tests*[1]

Drop height (feet)	Grain velocity[2]	Breakage at indicated moisture (percent) and temperature (F.) for—			
		Corn		Soybeans	
		12.6 at 25°	15.2 at 31°	11.0 at 32	12.6 at 50°
	F.p.m.	*Percent*	*Percent*	*Percent*	*Percent*
100	3,650	13.82	9.55	5.63	2.18
70	3,125	10.83	5.03	2.99	.97
40	2,420	5.86	.86	1.69	.37

[1] Based on stream from 8-inch orifice falling on concrete at 45° angle; 3 replications for each test condition.

[2] Predicted by equation based on linear regression analysis of experimental data (see fig. 8).

TABLE 15.—*Effect of grain stream velocity on breakage in grain-thrower tests*[1]

Belt speed (f.p.m.)[2]	Grain velocity[3]	Breakage at indicated moisture (percent) and temperature (F.) for—			
		Corn		Soybeans	
		13.2 at 49°	15.4 at 34°	11.1 at 39°	12.5 at 41°
	F.p.m.	*Percent*	*Percent*	*Percent*	*Percent*
3,810	2,135	5.13	1.42	—	—
2,880	1,935	2.75	1.15	—	—
1,800	1,325	1.57	.52	—	—
3,810	2,055	—	—	1.46	0.76
2,880	1,985	—	—	1.01	.56
1,800	1,335	—	—	.59	.38

[1] Average breakage for 3 bulkhead types at 10 feet from thrower discharge.

[2] Measured under load; no load belt speeds were 4,030, 3,030, and 1,889 f.p.m.

[3] Measured at 10 feet from thrower discharge.

REMEDIAL MEASURES

Two obvious approaches to reducing grain breakage from handling are to handle the grain more gently and to make it tougher and less subject to breakage.

One way to reduce breakage is to handle grain at as high a temperature and moisture content as possible. For example, breakage averaged about 4.6 percent less when corn was dropped at 15.2-percent moisture rather than at 12.6-percent moisture. However, the storage life is increased at lower grain temperatures and lower moisture contents. These conditions are opposite to those indicated for best handling.

The grain damage in this study was due largely

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to impact. Reducing the grain velocity at impact and providing more resilient impact surfaces appear to be the most promising approaches to gentler handling. Reducing drop height showed the greatest potential for breakage reduction in commercial grain handling (fig. 11). In many instances the sum of the breakage from three or more drops of 40 feet was less than the breakage from a single drop of 100 feet.

Table 16 gives an index that was calculated to relate the breakage in drops of 40 and 100 feet for all the corn and soybean tests. Any value in the table larger than 2.5 (100 divided by 40) suggests that breakage could be reduced by limiting the drop height to 40 feet. The information in table 14 also shows that reducing the drop height was more effective at the higher moisture contents with corn, since this grain could be dropped more times from 40 feet without exceeding the damage from one drop of 100 feet. Probably for dry corn that is very brittle, drop heights should be less than 40 feet, the minimum in these tests.

Grain-thrower breakage can be minimized by reducing belt speeds and thrower distances so that grain velocities upon impact are well below 2,500 f.p.m. (see table 13).

The impact surfaces used in this study had only a moderate effect on the amount of breakage. Dropping corn on corn rather than on concrete reduced the average breakage from 7.7 to 6.0 percent. However, Keller et al. (*11*) found that corn kernel damage with a urethane impact surface was only one-fifth that with concrete. Whenever feasible, grain should be allowed to impact on other grain or on surfaces more resilient than concrete.

Increasing the size of the grain stream in free fall resulted in less breakage in this study. This result suggests the use of as large a discharge orifice as feasible for any particular grain-handling method. Also, there was some evidence that confining the grain stream so there is less individual kernel impact may be effective in reducing breakage.

In spouting, all projections should be kept out of the path of the grain stream.

Although some of the breakage levels in this report were high, especially in the drop tests with corn, it should be remembered that some of the tests represented the most severe conditions in commercial grain handling. In filling a bin, for example,

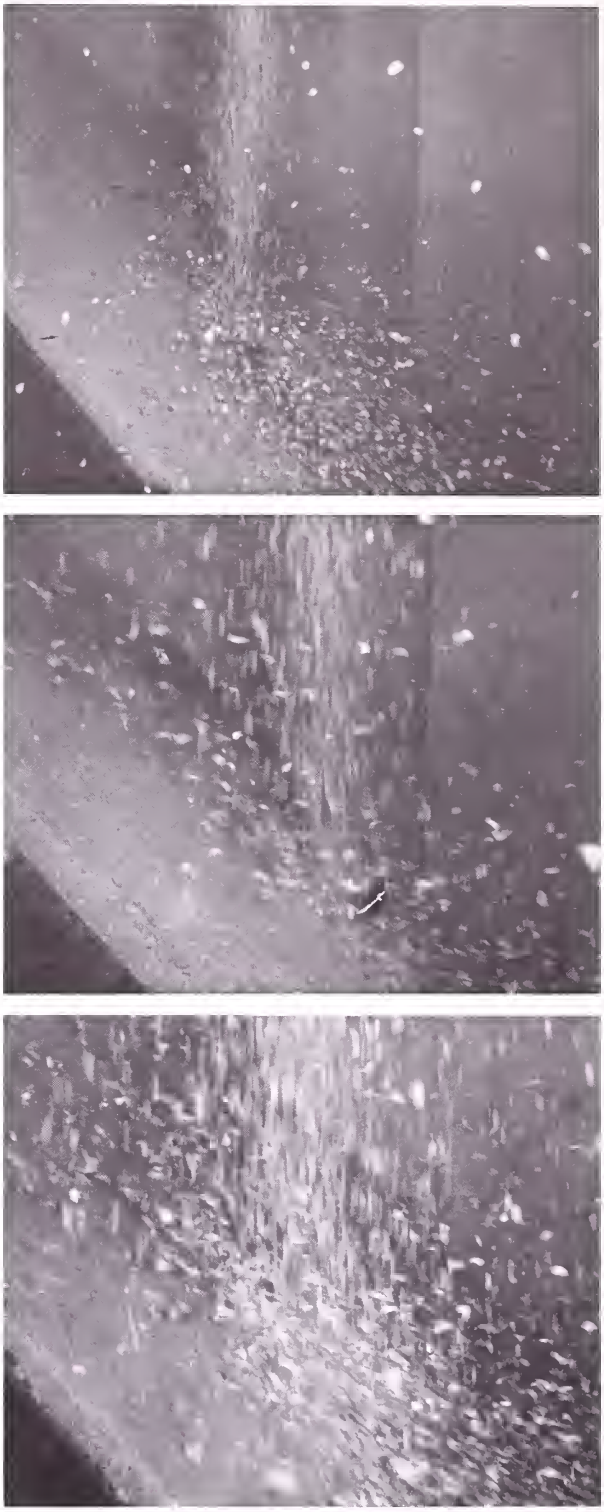

FIGURE 11.—Corn streams impacting concrete after free fall of 40, 70, and 100 feet (top to bottom).

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TABLE 16.—*Drop index*[1] *for corn and soybeans*

Handling method and test condition	Drop index at indicated moisture (percent) and temperature (F.) for—				
	Corn		Soybeans		
	12.6 at 25°	15.2 at 31°	11.0 at 32°	10.7 at 40	12.6 at 50°
Free fall					
Concrete impact:					
12-inch orifice	3.3	25.4	4.5	5.2	5.8
8-inch orifice	2.4	11.1	3.3	5.0	5.9
Grain impact, 8-inch orifice	2.9	28.4	3.9	5.6	5.1
Spouting					
Spout end:					
Bifurcated	2.8	8.5	2.2	3.1	2.8
Flex turn	3.0	10.2	2.2	2.5	1.9
Flex turn with bar	2.6	8.2	2.2	3.0	2.2

[1] Number of times grain may be dropped 40 feet without exceeding breakage in single drop of 100 feet.

the floor is covered quickly, and as the bin is filled the drop height is reduced. Thus, the average breakage in filling a bin would be less than the amounts given in this report. However, in repeated handling, the cumulative breakage may exceed the levels reported.

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APPENDIX

Table 17.—*Breakage in grain from free-fall and spouting drop*

Drop height (feet)	Discharge orifice diameter	Impact surface	Spout end	Breakage[1] in grains tested at indicated moisture (percent) and temperature (F.)									
				Corn		Soybeans			Spring wheat		Winter wheat	Pea beans	
				12.6 at 25°	15.2 at 31°	11.0 at 32°	10.7 at 46°	12.6 at 50°	11.2 at 27°	12.9 at 34°	11.1 at 45°	16.9 at 47°	15.5 at 62°
	Inches			*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Free fall:													
100	12	Concrete	—	12.01	6.87	4.01	3.2	1.40	0.36	0.15	0.21	—	—
70	12	do	—	7.07	2.54	1.82	1.23	.56	.19	.11	.18	—	—
40	12	do	—	3.59	.27	.89	.62	.24	.16	.12	.15	—	—
100	8	do	—	13.82	9.55	5.63	5.72	2.18	.34	.16	.29	13.64	—
70	8	do	—	10.83	5.03	2.99	2.22	.97	.20	.11	.18	—	—
40	8	do	—	5.86	.86	1.69	1.15	.37	.16	.12	.18	.82	1.01
100	8	Grain	—	12.53	7.11	4.06	4.11	1.39	.29	.16	.14	—	—
70	8	do	—	7.74	4.00	1.89	1.68	.62	.22	.11	.08	—	—
40	8	do	—	4.35	.25	1.05	.74	.27	.16	.13	.11	.16	.89
Average free-fall tests				8.64	4.05	2.67	2.30	.89	.23	.13	.17	4.87	.95
Spouting:													
100	8	Steel	Bifurcated	8.32	2.22	1.82	1.57	.59	.23	.14	.14	3.50	1.26
40	8	do	do	2.97	.26	.82	.50	.21	.19	.14	.09	—	—
100	8	do	Flexible turn	7.02	1.53	1.45	1.32	.41	.21	.10	.12	—	—
40	8	do	do	2.37	.15	.67	.53	.22	.14	.15	.12	—	—
100	8	do	Flexible turn with bar	7.99	2.72	2.07	2.28	.65	.24	.14	.13	—	—
40	8	do	do	3.07	.33	.94	.75	.29	.16	.13	.13	—	—
Average spouting tests				5.29	1.20	1.30	1.16	.40	.20	.13	.12	3.50	1.26

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[1] Mean of 3 test replications. For procedure used to determine breakage, see p. 17.

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TABLE 18.—*Breakage in grain handled with grain thrower*

Thrower belt speed (f.p.m.)	Distance from thrower to bulkhead	Bulkhead material and position	Breakage[1] in grains tested at indicated moisture (percent) and temperature (F.)									
			Corn				Soybeans			Spring wheat		Winter wheat
			13.2 at 49°	12.8 at 78°	15.4 at 34°	15.0 at 76°	11.1 at 39°	12.5 at 41°	10.7 at 61°	11.1 at 36°	12.9 at 47°	10.8 at 44°
	Feet		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
4,030	10	Steel, vertical	5.53	1.98	1.66	0.94	1.49	0.84	0.77	0.15	0.13	0.14
4,030	10	Steel, horizontal	4.52	2.57	1.18	.83	1.43	.77	.64	.20	.14	.18
4,030	10	Wood, vertical	5.34	2.27	1.41	.97	1.47	.67	.51	.27	.14	.22
4,030	25	Steel, vertical	3.32	1.78	1.16	.60	1.62	.64	.77	.23	.15	.10
4,030	25	Steel, horizontal	3.54	1.59	.88	.52	1.28	.69	.66	.23	.17	.08
4,030	25	Wood, vertical	2.86	1.79	.74	.60	1.21	.74	.60	.15	.13	.13
4,030	40	Steel, vertical	2.88	2.08	1.04	.61	1.08	.67	.60	.23	.17	.09
4,030	40	Steel, horizontal	3.60	2.45	.78	.58	1.20	.64	.61	.20	.21	.11
4,030	40	Wood, vertical	2.00	1.51	.65	.57	1.01	.60	.51	.14	.12	.11
3,030	10	Steel, vertical	2.81	1.80	1.07	.76	1.09	.57	.29	.12	.14	.10
3,030	10	Steel, horizontal	2.53	1.65	1.30	.58	.98	.60	.35	.15	.10	.15
3,030	10	Wood, vertical	2.90	1.69	1.07	.70	.95	.50	.29	.22	.17	.20
1,889	10	Steel, vertical	1.56	.75	.55	.39	.61	.40	.40	.13	.14	.08
1,889	10	Steel, horizontal	1.67	.67	.43	.32	.56	.38	.27	.16	.08	.12
1,889	10	Wood, vertical	1.47	.79	.58	.35	.60	.37	.23	.21	.15	.18
Average all tests			3.10	1.69	.97	.62	1.11	.61	.50	.19	.14	.13

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[1] Mean of 3 test replications. For procedure used to determine breakage, see p. 17.

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TABLE 19.—*Breakage in grain handled with bucket elevator*

Belt speed (f.p.m.)	Boot feeding method	Bucket loading	Bucket style	Breakage[1] in grains tested at indicated moisture (percent) and temperature (F.)										
				Corn			Soybeans			Spring wheat		Winter wheat	Pea beans	
				13.3 at 43°	12.7 at 85°	15.1 at 28°	14.8 at 84°	10.8 at 58°	12.6 at 43°	10.9 at 28°	12.9 at 36°	11.5 at 48°	15.5 at 63°	17.2 at 53°
				Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
650	Front	1/2 full	Nu-Hy	3.18	1.06	1.17	0.30	0.42	0.43	0.11	0.11	0.13	—	—
650	do.	Full	do.	2.74	.68	.92	.21	.22	.25	.11	.16	.13	—	—
940	do.	1/2 full	do.	2.89	1.06	1.30	.33	.43	.34	.17	.15	.12	—	—
940	do.	Full	do.	2.68	.95	.80	.26	.53	.37	.15	.16	.13	—	—
650	Back	1/2 full	do.	2.21	1.03	.78	.20	.32	.27	.11	.17	.11	—	—
650	do.	Full	do.	1.64	.81	.28	.19	.22	.24	.11	.14	.12	—	—
940	do.	1/2 full	do.	2.01	.90	.41	.24	.42	.27	.12	.12	.10	—	—
940	do.	Full	do.	2.67	.82	.29	.29	.51	.28	.33	.11	.20	—	—
650	Front	1/2 full	Link belt	2.95	1.06	1.00	.21	.37	.36	.15	.15	.11	—	—
650	do.	Full	do.	2.81	.79	.35	.18	.37	.32	.17	.13	.14	0.84	0.25
940	do.	1/2 full	do.	3.03	.96	.39	.32	.46	.40	.18	.13	.10	—	—
940	do.	Full	do.	2.36	.89	.82	.35	.40	.33	.22	.12	.08	—	—
650	Back	1/2 full	do.	2.48	.67	.24	.38	.29	.24	.15	.12	.13	—	—
650	do.	Full	do.	2.26	.65	.20	.22	.30	.24	.16	.12	.10	—	.15
940	do.	1/2 full	do.	2.67	1.38	.79	.28	.68	.33	.18	.12	.18	—	—
940	do.	Full	do.	1.98	.92	.83	.31	.51	.26	.19	.12	.20	—	—
Average all tests				2.54	.91	.66	.27	.40	.31	.16	.13	.13	.84	.20

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[1] Mean of 3 test replications. For procedure used to determine breakage, see p. 17.

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